



Investigating the Influence of Material Properties, Infiltration, and Climatic Conditions on Hygrothermal Risk of Building Envelopes

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Abstract. Deterioration of building envelopes due to poor moisture management is considered critical in the sustainability of buildings where wood-frame constructions are widely used. However, the integration of research outputs in building enclosure design analysis considering the combined effects of internal and external parameters is less exhaustively explored. This is partly due to the uniqueness of each component material, the uncertainty of involved factors, and complex interdependencies that influence the response of building envelopes throughout their service lives. To address this issue, hygrothermal simulations and risk assessment of key moisture indicators were performed on wall assemblies exposed to different climatic conditions. The assessment focused on three major issues concerning the moisture design of exterior walls: (1) selection of appropriate materials for optimum performance, (2) effect of moisture infiltration, and (3) different geographic locations. The proposed design methodology includes the simulations and development of a design experiment method based on full-factorial design. The proposed method demonstrates a quantitative appraisal resulting in a clear presentation of moisture accumulation, considering dependencies on various factors. Research findings showed several important factors that affect the hygrothermal performance of wood-frame wall assemblies and need to be considered in the design process. The relationship with the external climate determines the optimal moisture response, given the dependency of the component properties on the drying and wetting potential.

Keywords: Building physics; Biodeterioration risk; Green and healthy building; Hygrothermal analysis; Wood-frame building envelopes

1. Introduction

The concept of sustainable building design has gained importance in recent decades, as manifested by green and healthy building strategies (Wardhana, Berawi, and Sari, 2023; Doan *et al.*, 2021; Isa *et al.*, 2018). Sustainable design, which can be interpreted as creating a healthy built environment using resource-efficient and ecologically based principles, has encouraged the establishment of improved design criteria for modern buildings. Consequently, modern buildings are becoming increasingly complex, such as in their heat-air-moisture (HAM) design (Sehizadeh and Ge, 2016). Functional variations have facilitated this complexity, the inclusion of several ventilation systems, and the use of novel building materials. In this sense, the moisture design of the building envelope plays a key role in determining the performance of a building, considering the envelope's features as the first line of defense and the main interface of buildings with the external environment.

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Uncontrolled moisture accumulation in building envelopes is a major concern in building practices where wood-frame wall construction is widely used, such as in Canada. Moisture deteriorates the structural integrity and thermal performance of its components through biological, mechanical, and chemical degradation processes (Hussain, Shamraiz, and Abrar, 2016). Mold growth, rotting of stud cavities and other wood-based products, swelling and disintegration of cladding, and rusting of fasteners are examples of moisture-induced wall degradations. Moreover, excessive moisture in the building envelope can create an environment that promotes the growth of hazardous organisms, potentially posing a health risk to occupants.

Effective moisture management, in principle, entails minimizing moisture entrance into the system and maximizing moisture departure when it enters the system. The long-term performance of the wall assembly is a consequence of heat, air, and moisture transport within the assembly under specific environmental conditions, known as hygrothermal performance. This performance considers the response of the wall as a whole and the localized responses of any of its components and material layers. However, the effect of material characteristics on moisture response is still openly discussed and debated. Yamamoto and Takada (2022) stated that the hygrothermal characteristics of materials in the numerical analysis of simultaneous heat and moisture transfer will vary depending on the data source employed. The analysis is commonly governed by prescriptive criteria owing to the complexity of the problem and lack of conclusive indicators (Mukhopadhyaya et al., 2006; Mukhopadhyaya, 2003).

The objective of this study is to investigate the effect of material combinations and the corresponding risk of wood-frame exterior wall designs using hygrothermal simulations and a design experiment approach. The outputs from the simulations were processed and analyzed to provide extensive information using the RHT index, moisture content (MC) in the region of interest of wall components as response indicators, and Moisture Index (MI) as a climate indicator. The findings presented in this paper help address a number of concerns regarding the importance of the impact of components and material layers on the overall moisture performance of wood-frame wall constructions.

2. Methods and Materials

The methodology used to assess the hygrothermal risk of wood-frame exterior wall assemblies is presented in the scheme depicted in Figure 1. The methodology consists of three main steps: input and pre-processing, simulation, and post-processing. In this study, the output of the assessment model is presented in the form of accumulated moisture transfer (including RHT-index, MC, and MI), facilitating a comparative risk analysis between models.

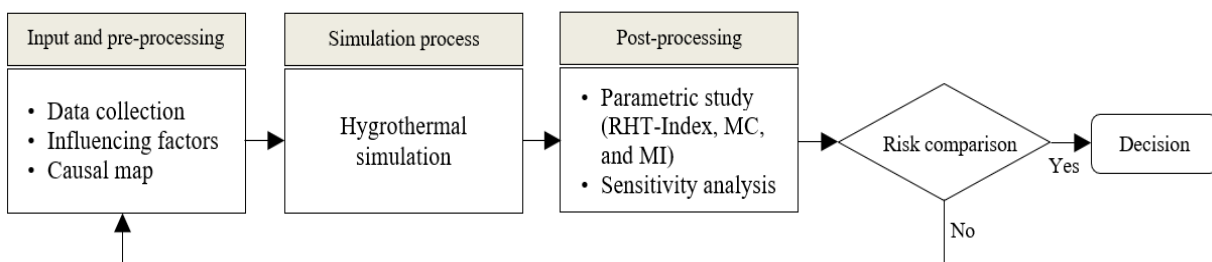


Figure 1 Methodology of hygrothermal risk assessment

To capture interdependencies, full factorial design was used to statistically filter out the significant parameters and significant interaction between parameters. The findings

from the parametric study were further analyzed, exploring the characteristics of these parameters in subsequent analyses. A full factorial design is a type of sensitivity analysis whose design consists of two or more factors, each with discrete possible values or levels that take all possible combinations of those levels across all factors (Ryan, Koltsakis, and Manoleas, 2019). This analysis allows the users to study the effect of each factor in a model, as well as the effects of interactions between factors, on the response variable. The parametric study conducted in this research was classified as a multi-level full factorial with four factors. To evaluate the result of a factorial design, a graph of factor interaction plot was created. This analysis was performed with *MATLAB* (Supplementary File— S01).

2.1. Input and Pre-processing

2.1.1. Data collection

- *Wall construction details*

This study focused on wood-frame walls with two commonly used claddings in North America: brick veneer and stucco. The basic details of the construction of the wood-frame structure wall are based on the reference model (Lstiburek, 2002) and are shown in Figure 2. The wall configuration remained the same for all the simulations performed in this study, with certain parameters being varied for the parametric study.

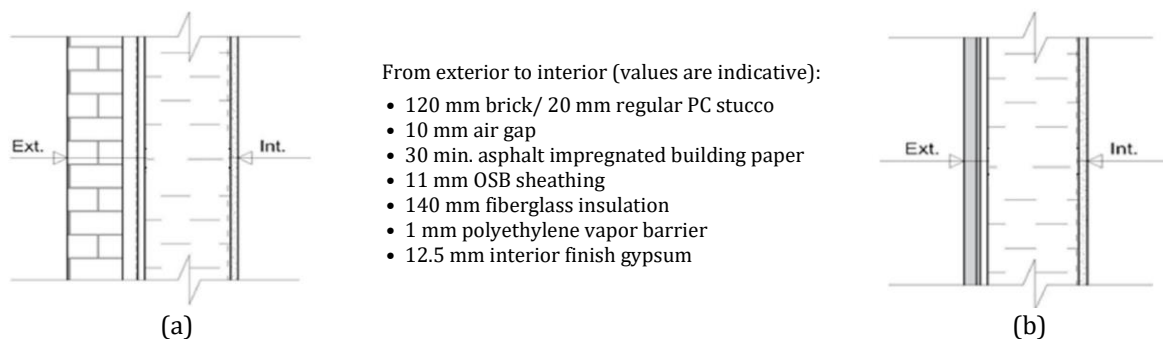


Figure 2 Basic construction details: (a) brick wall and (b) stucco wall

- *Boundary conditions and geographic location*

The two main boundary conditions were the outdoor and indoor conditions. The outdoor boundary condition was defined by the specific weather data obtained from the reference year files (Cannon, 2016). The climate analysis module includes geographical location data and several major weather components, such as temperature, relative humidity, short- and long-wave radiation, wind velocity, wind direction, annual rainfall, cloud index, and air pressure, recorded on an hourly basis.

The hourly indoor climatic conditions (i.e., temperature and relative humidity) were derived from the standard year climate based on ASHRAE Standard 160 (ASHRAE, 2016) in heating-only mode, in which the indoor temperature is kept constant at 22°C during winter (heating season) and left to fluctuate during summer (cooling season). For indoor relative humidity, summer and winter settings were simulated using the ASHRAE simplified model, which depends on exterior climate conditions. A total exposure duration of three years was used for the simulation. The initial year of the simulation was considered a conditioning period and thus was not taken into account in the calculations of the response variable.

- *Moisture entry due to moisture infiltration*

Convective moisture entry induced by air movement through defects in the air control layer is a complex and multidimensional effect (Glass *et al.*, 2017). In this study, the accidental moisture entry was modeled by a convective moisture source. The model allows a transient consideration of the vapor infiltration through air flow, depending on the

specific air permeance of the component on the height of the connected airspace that accounts for the air pressure due to the stack effect. Component permeance estimates in the DIN 68800-2 (DIN, 2012) assume that moderately airtight buildings correspond to the air convection responsible for 250 g/m² of condensation in insulated wooden structures during winter. Therefore, this value was selected. Regarding the position of the convective moisture source describing the condensation layer, the oriented strand board (OSB) sheathing layer facing the cavity was selected for this purpose. The air pressure difference was obtained from the assumption of height for a single-family home ($h = 5$ m).

2.1.2. Determination of the influencing factors

The relevant physical processes were considered while selecting the influential parameters for this study. The design suggested keeping the insulation constant since this has been extensively explored. In Pallin (2012), the parameters responsible for the material behavior were examined with a specific purpose on the effect of layer properties on the energy performance. Based on the research, the important factors in moisture problems were driven by two mechanisms: wind-driven rain and undercooling.

A causal map (Ackermann and Alexander, 2016) is proposed to depict the major cause-effect in hygrothermal response and presented in the *Supplementary File—S02*. The vapor barrier properties, rain screen, moisture leakage resulting from vapor infiltration, and the diffusivity of the cladding material were identified as highly significant factors influencing moisture diffusion and undercooling processes. Therefore, the following parameters were investigated: 1) Vapor barrier permeance— varied between 0.1 perms and 20 perms (no vapor barrier) (ASHRAE, 2016; Mukhopadhyaya, 2003); 2) Rain screen— varied between 0 mm (no rain screen) and 25 mm; 3) Moisture leakage— varied between 0 g/m² (no moisture leakage) and 250 g/m² (moderate airtightness building) (DIN, 2012); and 4) The cladding material diffusion resistance factor— varied between 169 (typical value for brick) and 311 (typical value for regular PC stucco) (Fraunhofer IBP, 2022).

2.2. Simulation Process and Post-Processing

2.2.1. Hygrothermal simulation and parametric study

Hygrothermal simulations and subsequent analyses were performed to characterize the role of the specified material layers in the moisture performance. Simulations were performed using the hygrothermal simulation program WUFI® Pro V6.6. A parametric study was performed by investigating the effect of varying the component parameters and climatic conditions on the overall long-term moisture response of the wood-frame wall assembly. By doing so, the significance of individual factors and the interaction between these factors on the hygrothermal performance of the exterior wall could be understood.

The parametric analysis focused on three important issues concerning the moisture design of exterior walls: (1) materials properties, (2) effect of moisture infiltration, and (3) different geographic locations. A set of variable values was assigned within a certain range for each parameter. A total of 144 simulations were conducted at this stage, as shown in the *Supplementary File—Table S03*. Results in ASCII format were extracted and transformed in the post-processing stage for subsequent analyses.

3. Results and Discussions

3.1. Simulation Process

The typical outputs considered for the analyses were the RH and T graphs across the wall assembly over the simulation period (*Supplementary File—S04*). To determine the distributions of RH and T for each wall component and across the region of focus, the output data were extracted and plotted using the relevant indices.

3.1.1. RHT Index calculation

The RHT index (Kumaran *et al.*, 2003; Mukhopadhyaya, 2003; Mukhopadhyaya *et al.*, 2002) is a comparative metric able to quantify the hygrothermal response of specific part of the building envelope accumulatively over a long period. This index can be used for quantification of the localized hygrothermal response in terms of the amount (how much) and of the time (how long). The part of the wall component under consideration is called the ‘region of interest’ or ROI, which can be defined as a region of the wall's cross-section where the response is most severe. To calculate the RHT index at ROI, two values— RH and T —along specified time intervals are required. The generic definition of the RHT index is given as cumulative RH and T by the following expression:

$$\text{RHT Index} = \sum_{t=1}^n (RH - RH_x) \otimes (T - T_x) \tag{1}$$

where RH denotes relative humidity, T denotes temperature, and t denotes time step. RH_x and T_x are thresholds in which, at any time step, when either $RH \leq RH_x$ or $T \leq T_x$, the RHT value for that time step is zero. Figure 3 shows the wall cross-section and outputs at ROI.

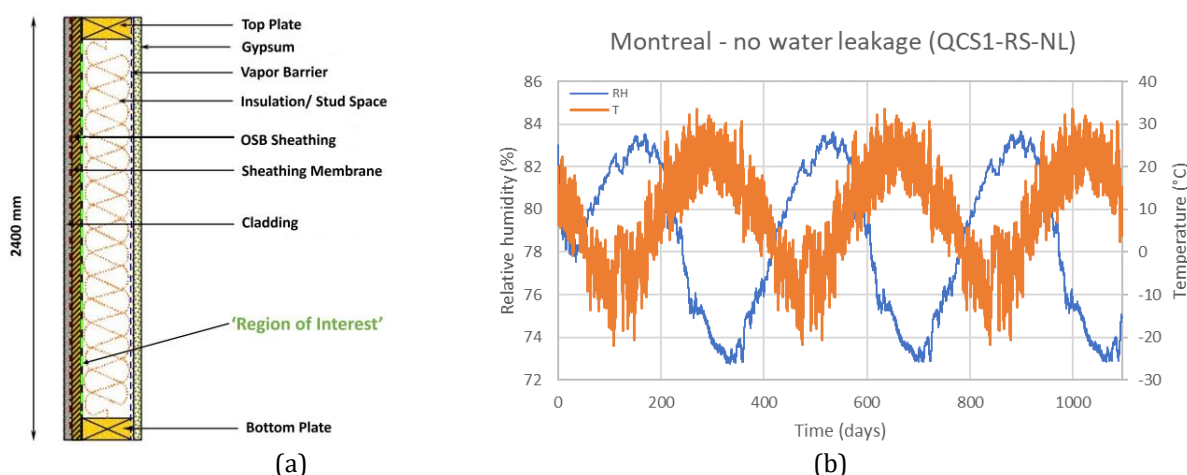


Figure 3 RH and T investigation: (a) wall section with “ROI” of OSB sheathing board layer facing stud cavity; (b) RH and T variation with time at the ROI

The results of the simulations provide an opportunity to closely examine the RH and T conditions inside the wall assembly over a specified period. Based on the observation of the part with the most severe moisture response, the OSB layer (Figure 3) serves as the ROI for all simulations in this study. In this case, in 1) user-defined threshold values of RH_x 95% and $T_x = 5^\circ\text{C}$ were selected (ASHRAE, 2021), and a time step of one hour was used. The threshold value indicates the critical condition when mold onset begins as a function of the duration of moisture accumulation.

3.1.2. Study of parameter influence on hygrothermal performance

- *Effect of water vapor leakage*

Plots of moisture response of wall models subjected to the Montreal climate are illustrated in Figure 4. In essence, the graph shows the most severe hygrothermal response present in the wall assembly. In this particular case, the RHT index of the wall with 1 perm VB has increased by 180% from 438 to 1226, owing to accidental moisture entry.

In order to know the temporal behavior of moisture accumulation, the evolution of MC over time was investigated (Figure 4b). The graphs demonstrated the comparable impacts on the wall assembly's MC response as a result of accidental moisture intake. Due to leakage, there has been a higher intensity of moisture content at ROI, which has led to a situation where MC may approach 15% mass during wetting seasons. However, the results show that the peak MC is always below the threshold of wood decay, i.e., 25% (ASHRAE,

2021), thus indicating a good moisture response. Moreover, the wall assembly shows a good drying potential in which the sheathing board does not store liquid moisture for a long period and, therefore, gives an indication of good moisture management.

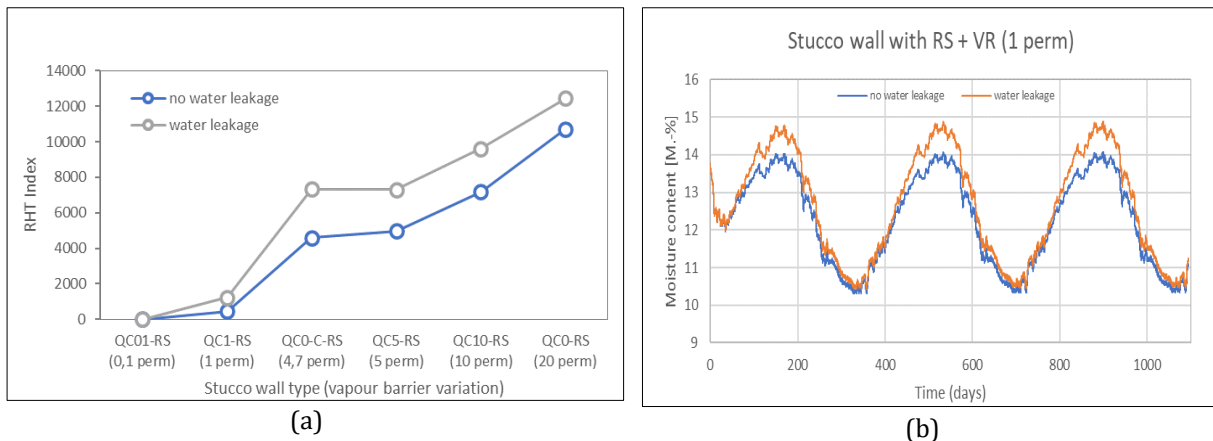


Figure 4 (a) RHT index at the ROI for stucco wall; and (b) Moisture content— MC (% mass) over simulation period with 1 perm vapor barrier, with leakage and with no leakage

• *Effect of vapor barrier permeance*

In the present study, the permeance of vapor barrier (VB) ranges from 0.1 to 20 perm. The highest value is associated with no vapor barrier plus coated gypsum board. As shown in Figure 5, The vapor permeance of VB has a considerable impact on the overall moisture response. A less-permeable VB can lessen the severity of the moisture response, whereas the VB with high permeance causes a severe moisture response (i.e., the highest RHT index).

In the case of the wall with no vapor barrier and coated interior gypsum only (corresponding to 4.7 perms), the layer brings a moisture response similar to those with 5 perm vapor barriers, thus verifying the model. It has been observed that the complete removal of the vapor barrier produces a much higher level of moisture response than the other cases. Therefore, the properties of vapor barrier have a significant effect on the moisture response, and a vapor permeance between [0.1:1.0 perm] would lead to an optimum moisture strategy in wall assemblies of the type represented in this study.

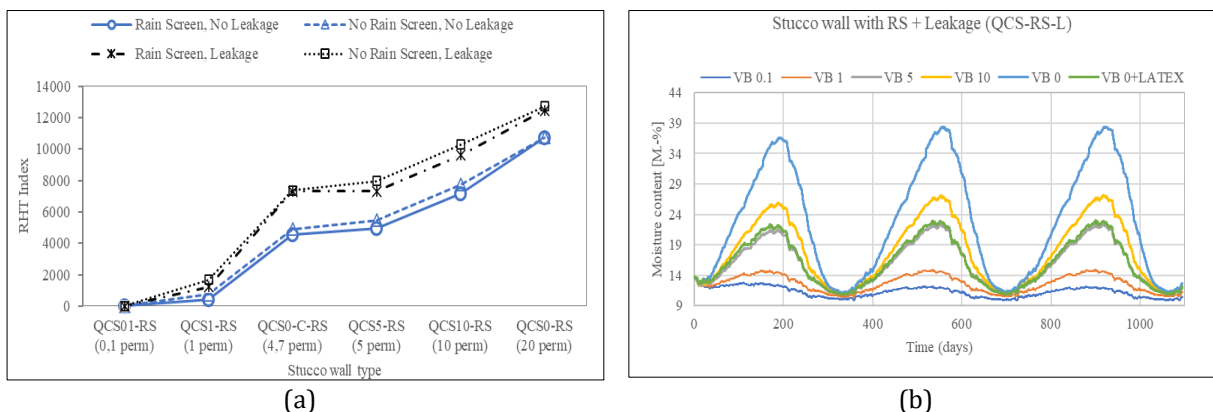


Figure 5 Moisture response due to different permeance of VB: (a) RHT index, and (b) MC

Results of moisture content show similar effects on the hygrothermal response for the wall assembly subject to varied vapor permeance, as shown in Figure 5b. The wall with a vapor barrier of 10 perms and those with complete removal of the vapor barrier has significantly higher moisture contents, above the decay threshold of 25%. The trend shows a slight increase over future time. However, the peak MC occurred for a relatively short period, where it decreased considerably during drying seasons.

• Effect of Exterior Cladding

Two cladding types, brick, and regular PC stucco, have been considered as cladding material. This part aimed to identify which of these two claddings provides sufficient moisture management. The results are presented in Figure 6. The graphs clearly demonstrate that the stucco cladding consistently shows a lower moisture response intensity (i.e., lower RHT index) for all vapor barrier permeances considered. Therefore, it is evident that for the conditions given in this study, the regular PC stucco provides an enhanced level of moisture performance Figure 6. After closely examining the cladding material characteristics, specifically those of stucco and brick (including heat capacity, dry density, air permeability, sorption properties, suction pressure, liquid diffusivity, and water vapor permeability), it was obvious that in this case, porosity and, consequently, water diffusivity, were the properties that differ most Figure 6.

In order to examine this effect, the exterior claddings with material whose diffusion resistance range from low extreme to high extreme were simulated. The result shows that the most optimum moisture response is provided by a certain range of cladding properties.

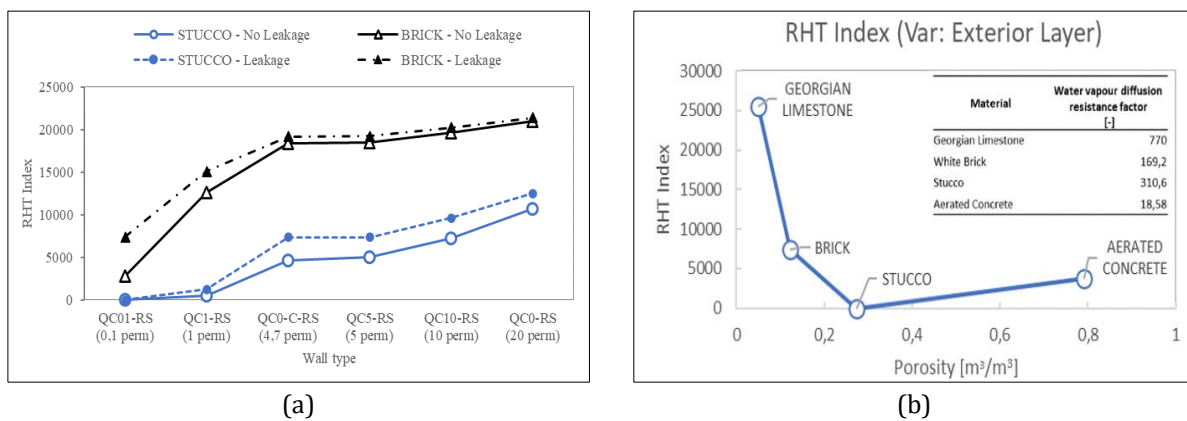


Figure 6 (a) RHT Index variation due to different permeance of vapor barrier with various configurations; (b) Varied porosity properties of cladding materials

• Effect of geographical locations

Three cities in North America, namely Montreal, Vancouver, and Miami, were chosen based on their moisture load characteristics. Moisture characteristics of a location can be expressed in terms of climate indices, e.g., the moisture index (MI). MI is calculated as a function of wetting potential (WI) and drying potential (DI) (Cornick *et al.*, 2002). In contrast to DI, which is based on annual evaporation potential, WI is computed based on annual rainfall. More severe moisture loading is indicated by a higher MI value.

Montreal, situated on the Atlantic coast of southeastern Canada, falls under the category of a humid continental climate. It experiences warm and humid summers, along with cold winters. Vancouver, located in the southwest corner of Canada, is a coastal city with a moderate oceanic climate. It is considered one of the warmest cities in Canada according to the Köppen climate classification. Moving on to Miami, its climate is classified as tropical monsoon. It is characterized by long and warm summers, hot and muggy winters, and a noticeably drier winter (Gaur and Lacasse, 2022).

The change in the RHT index with respect to the change in MI is shown in Table 1. The hygrothermal response of the wall changed as the intensity of the climate load did. Likewise, the RHT increased when accidental moisture was introduced into the stud cavity. However, the moisture responses of the models in Miami and Vancouver showed major differences despite their similar MI. This indicates a nonlinear and complex relationship between hygrothermal behavior and climate conditions (Ryan and Bristow, 2023).

Table 1 Moisture Index for three locations and the corresponding RHT Index

City	Moisture Index (MI) [-]	RHT95 (S1-RS-NL) [-]	RHT95 (S1-RS-L) [-]
Montreal, QC	0.93	0	0
Miami, FL	1.08	0	0
Vancouver, BC	1.09	1637	2239

To investigate this phenomenon, the authors observed the changes in MC over time for the wall assemblies in different locations, as shown in Figure 7. The right-handed figures show moisture content, whereas the left-handed figures show the outdoor climate conditions of the associated location. A significant difference was observed in the MC of the assembly in Miami, where the pattern was more irregular with a lower amplitude. This response corresponds with the temperature conditions in Miami, which fluctuate less (narrow amplitude) over the seasons, and these conditions support the drying process of the wall assemblies. The results are in line with those expected in relation to the moisture load in the respective region, where Vancouver has the highest moisture risk.

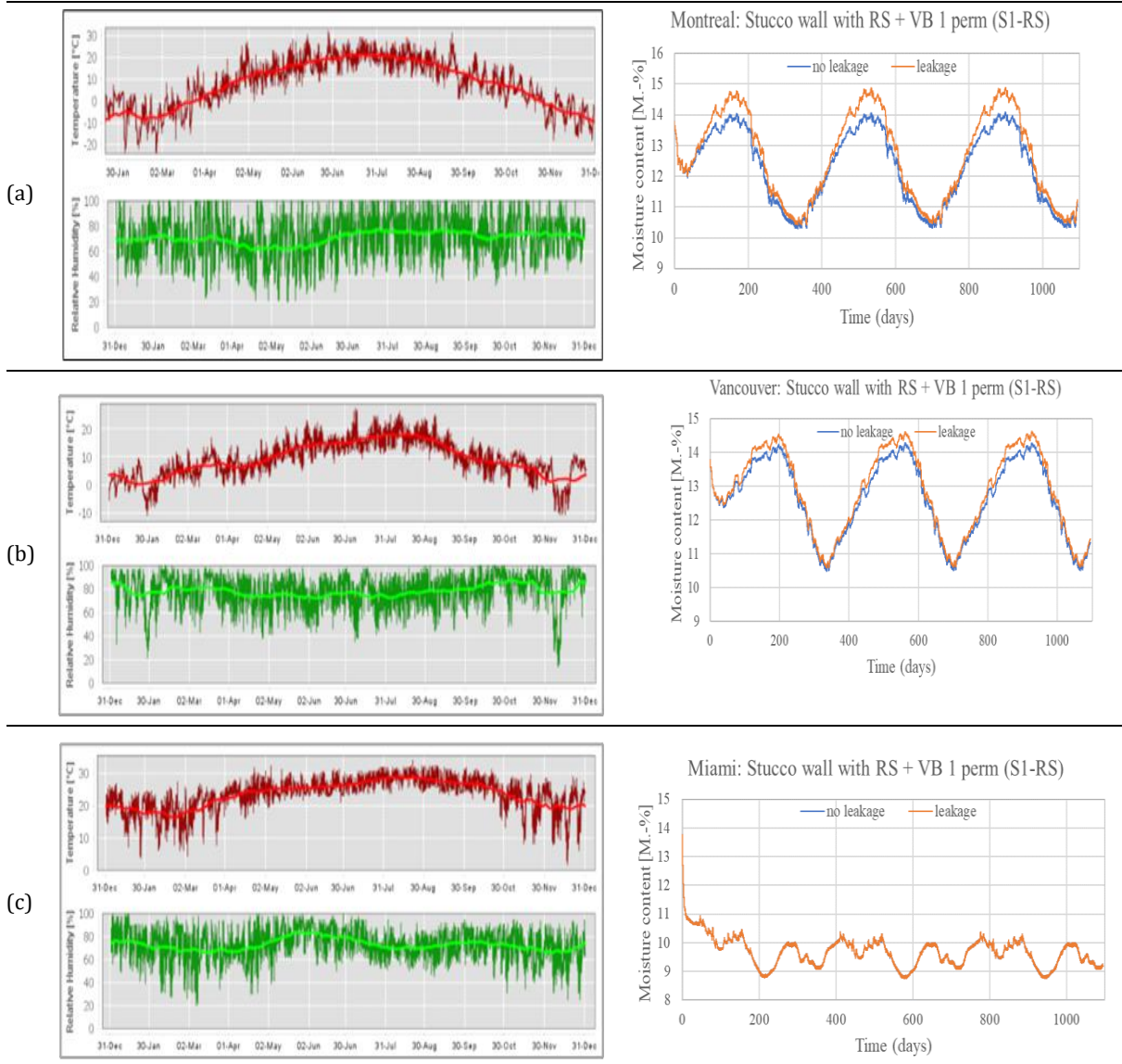


Figure 7 Moisture response (% MC) of the wall assemblies in relation to the outdoor climate conditions (T and RH): (a) Montreal; (b) Vancouver; (c) Miami

3.2. Sensitivity through Full Factorial Design

The factorial design plot in Figure 8 illustrates how major effects may be determined from the response variable and are related to the factors represented by the steepness of the plot lines. If the plot lines are not parallel, an interaction exists. The graphs display mean values where the mean values of RHT index were presented on the vertical axis, while input variables of each factor were presented on the horizontal axis (i.e., VB permeance, rain screen, moisture leakage, and cladding type). For example, the plot line with dotted yellow color represents the factor interaction of the model with VB permeance $VB = 20$. Meanwhile, the dotted green color and solid blue color plots represent models with VB permeance $VB = 1$ and $VB = 0.1$, respectively. Taking one point on the plot, e.g., $VB = 20$ and $RS = 1$, will give a mean value of the RHT index of that yellow-line model, which is 1.64×10^4 .

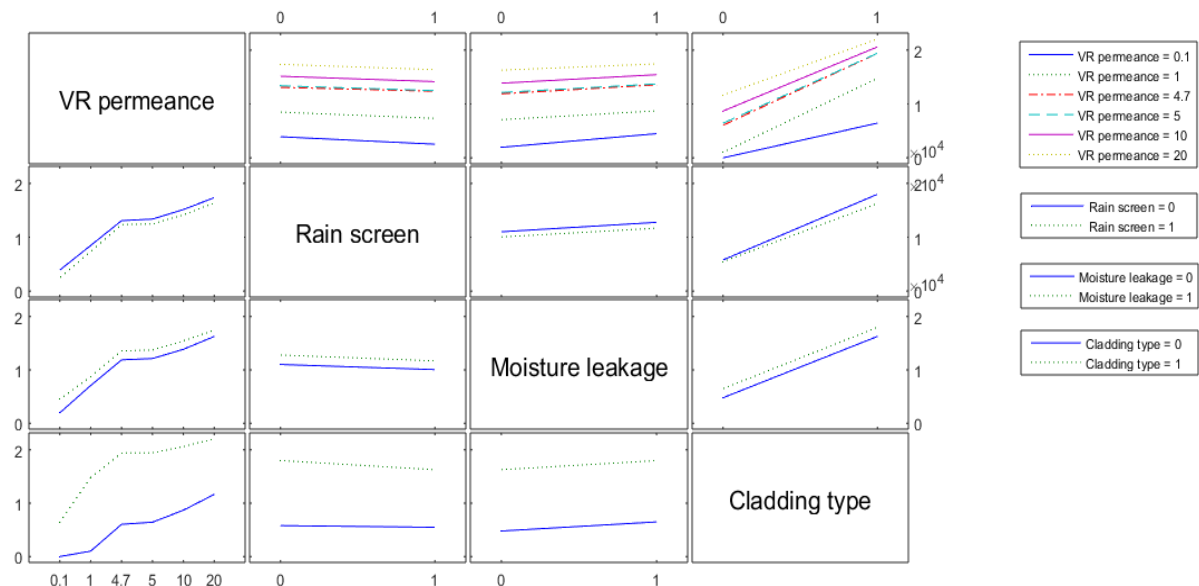


Figure 8 Interaction plot of factorial design. VB permeance varied to [0.1:20 perm]; Rain screen varied to 0 = without RS and 1 = with RS; Moisture leakage varied to 0 = without leakage and 1 = with leakage; Cladding type varied to 0 = stucco and 1 = brick

The interaction plot indicates that the vapor permeance and cladding parameters, followed by the moisture leakage parameter, have the greatest impact on the RHT index. The effect of moisture leakage in the form of moisture convection is significant in increasing moisture response and the corresponding biodeterioration risk, i.e., RHT index. Rain screen has relatively little influence. No strong interaction exists; however, the interaction of VB permeance–cladding type is the highest among all interactions.

The method applied in this study is an alternative to the analytical design method, e.g., the Dew Point Method (ASHRAE, 2016), which poses major limitations, such as only predicting condensation without knowing the magnitude and duration of moisture accumulation. Comparative sample calculation of this method is provided in the *Supplementary File—S05*.

4. Conclusions

The study investigated the biodeterioration risk of exterior walls induced by moisture accumulation through hygrothermal simulations. The findings from this study are summarized as follows. The effect of moisture leakage in the form of moisture convection significantly increases the moisture response and corresponding biodeterioration risk, i.e., the RHT index. However, the proper drying capacity provided by the barrier membrane can

maintain moisture transport within good magnitude (below mold decay threshold) and duration (short period of moisture storage). The effect of vapor barrier permeance is very important where a certain range of VB permeance provides optimum moisture responses. Together with cladding material, the interactive effect of those layers is decisive in a way that higher water vapor permeance and solar absorptivity of the exterior cladding can help dry out the water that has leaked into the wall assembly. Moreover, the VB permeance will affect moisture content in interior gypsum and cladding as moisture buffers. The effect of rain screens on the studied walls however is not decisive. Additionally, the moisture response of the exterior wall system was also closely correlated to the climatic moisture load in the respective region. Thus, careful analysis should be made in relation to climate conditions and their impact on the wall parameters. This relationships with the external climate determine the hygrothermal response, given the dependency of the component properties on drying and wetting potential. As such, knowledge of the roles of material layers on the overall moisture performance of building envelopes is essential to support design analysis for optimum moisture management. Future work will include developing a probabilistic method of moisture risk on building envelopes to account for uncertainties and applicability that has generic model for quantifying the risks.

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